Open Manufacturing strategy for accelerating metals additive manufacturing

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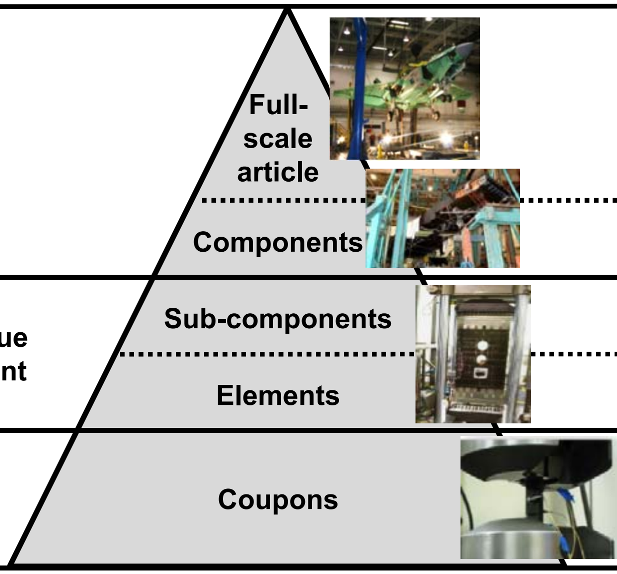
DARPA

Typical DoD qualification/certification approach

Building Block Test Structure Required for Certification



size scale	Level	Specimen Count	Cost ($M)	Time (Yrs)
Analysis validation	Full-scale article	2-3	100-125	4
Analysis validation	Components	10-30	10-20	3
Design-value development	Sub-components	25-50	10-35	3
Design-value development	Elements	2000-5000	10-35	3
Material property evaluation	Coupons	5000-100,000	8-15	2

Comprehensive understanding of manufacturing variation at different scales is needed

Current approach does not capture impact of manufacturing variability across all size scales

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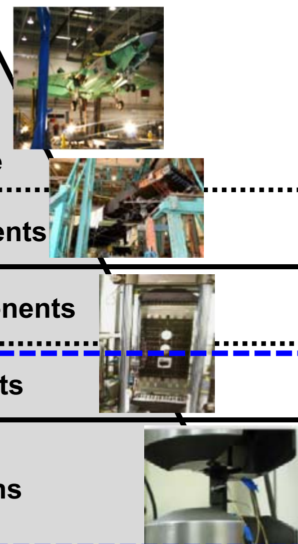
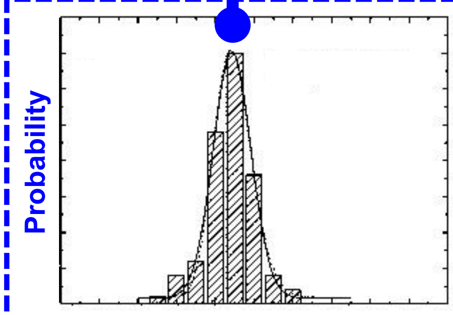


size scale

- **Collect statistically valid populations of properties for small size specimens**
- **Base larger scale structure designs on <u>measured material character</u>**



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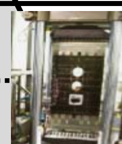

Effects of scale-up are not captured until the sub-component / component level testing

Redesign/Rework Iterations result in budget escalation and schedule delays

Impact: Contemporary platforms reuse traditional approaches to reduce the cost and risk of qualifying new technology

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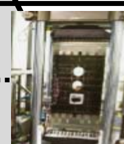


Manufacturing Process (foundation)

Effects of scale-up are not captured until the sub-component / component level testing

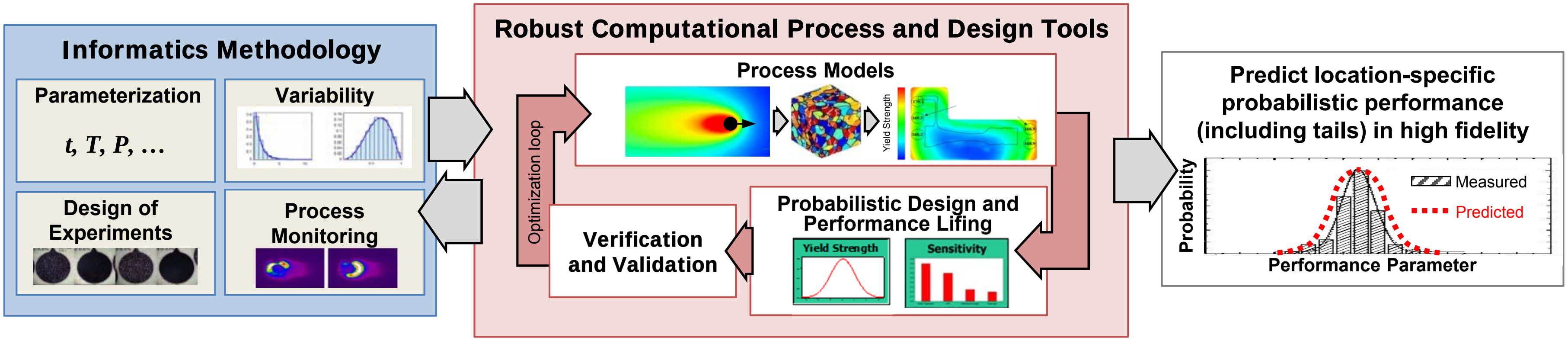
Redesign/Rework Iterations result in budget escalation and schedule delays

Impact: Contemporary platforms reuse traditional approaches to reduce the cost and risk of qualifying new technology

Impact of Manufacturing Parameters and Variability on material properties are never captured, understood, or controlled

Comprehensive understanding of manufacturing variation at different scales is needed

Open Manufacturing fundamentally changes how manufacturing variability is captured, analyzed and controlled



- Fully parameterize and monitor the factory-floor
- Capture probabilistic variability in laboratory and manufacturing environments

- Computational tools incorporate probabilistic variation into input parameters
- Rapid qualification schema that employ statistical methods for high-confidence prediction
- Rigorous model verification and validation
- Probabilistically predict location-specific process and part performance

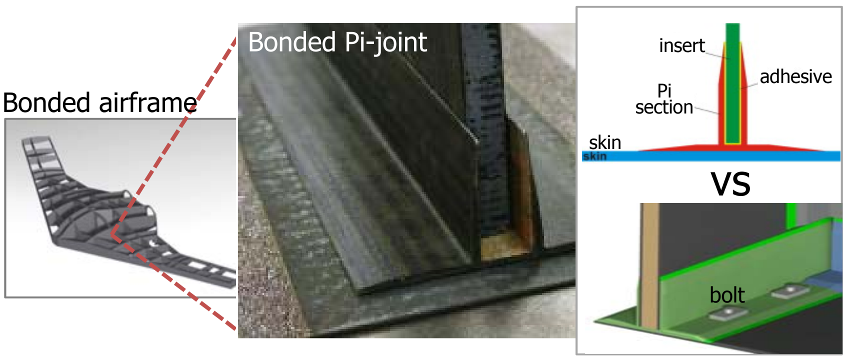
- Framework for rapid qualification
- Identify bounds of process window
- Build confidence in new technologies
- Optimize and control processes

Open Manufacturing Focus Technologies

Two focus technologies chosen to apply and validate OM methodologies

Bonded Composite Structures

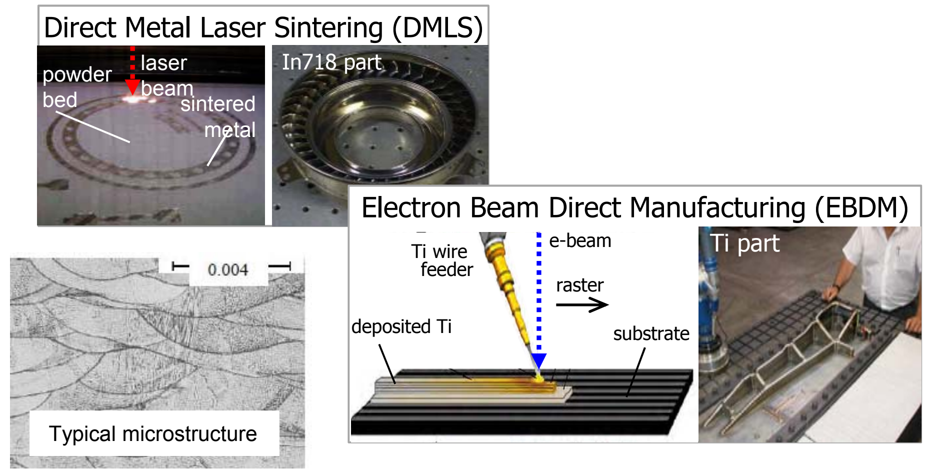
Holy grail for composite community for last 30 years



- Bonded composites allows unitized structure with lowered labor and reduced schedule
- Manufacturing process is not equipped to capture all variability
- Therefore, certifiers and designers don't have confidence that the process is well-controlled
- Bolts are added after bonding
- 7 performers

Metals Additive Manufacturing

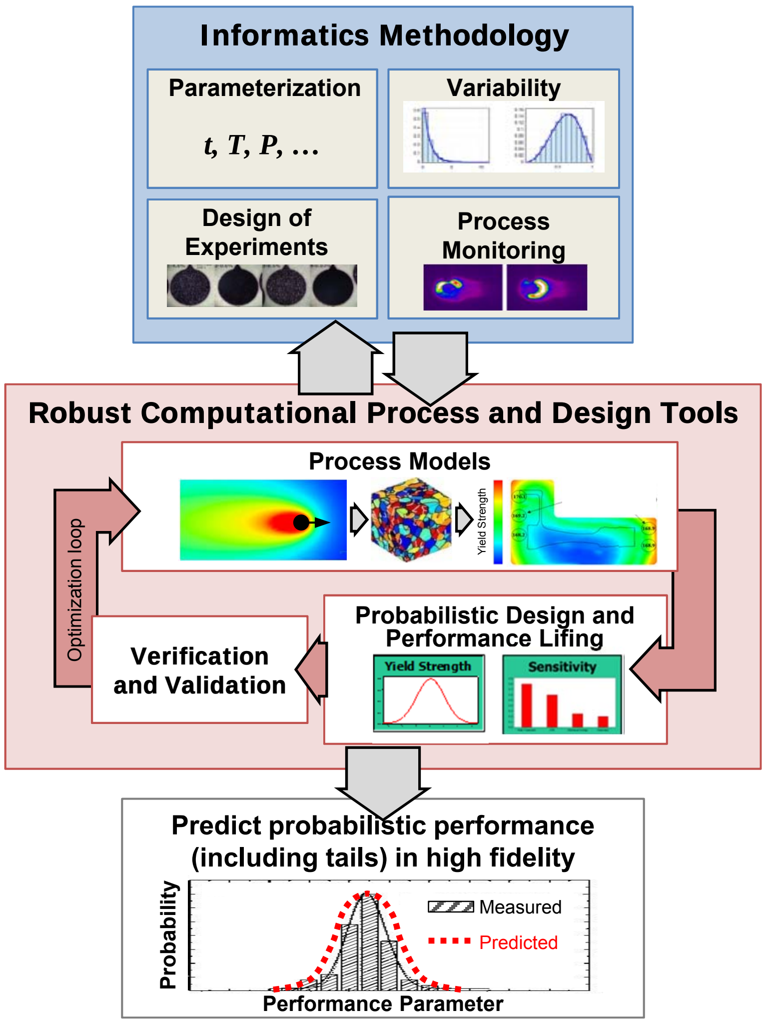
Emerging technology that is stuck with limited transition



- Reduces material usage, eliminates costly and lengthy tool development, and provides design freedom
- Cost benefits of additive manufacturing are negated by high cost of traditional "make and break" qualification
- 5 performers

Accelerate the manufacturing innovation timeline for these high impact processing technologies to unlock design and higher performance opportunities

Projects fully exercise the OM methodology



Honeywell DMLS In718+

- Direct Metal Laser Sintering (DMLS) of In718Plus
- Extend **Integrated Computational Materials Engineering (ICME)** concepts into probabilistic design and lifing methodology for DMLS to serve as a new paradigm for rapid qualification

ab initio first principles

Boeing TiFab

- Electron Beam Direct Manufacturing of Ti-6Al-4V (EBDM)
- Fully explore EBDM process window with **phenomenological metallurgical process models** and minimal testing to determine the key parameters that impact quality of manufactured product

empirically-based models

Lockheed Martin TRUST

- Out of autoclave bonded polymer reinforced composite aircraft structures
- Bayesian methods combine **a priori models (initially based on expert knowledge)** with observed shop floor data to iteratively inform models, compute confidence, and enable enhanced bond process control

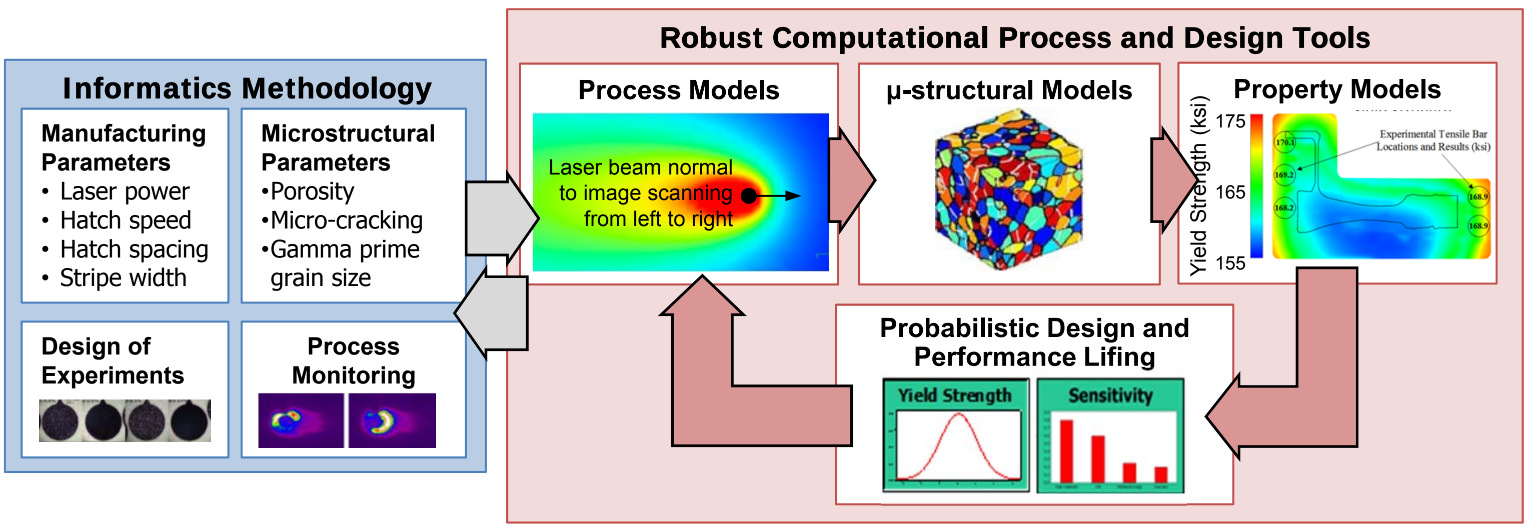
a priori models not physics based

Rapid qualification of powder bed fusion additive manufacturing

Direct Metal Laser Sintering (DMLS) of Inconel 718+ (Ni-Cr superalloy)
Take the process from laboratory to industry

Rastered laser beam sinters/consolidates metal powder to create high resolution structural parts

- Physics-based models of the transient process, microstructural evolution, and resultant properties
- Use DMLS machine parameters to optimize design, process, and material

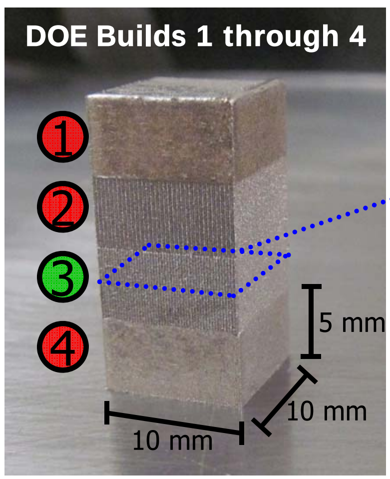


Extend Integrated Computational Materials Engineering (ICME) concepts into probabilistic design and lifing methodology to serve as a new paradigm for rapid qualification

Informatics for additive manufacturing

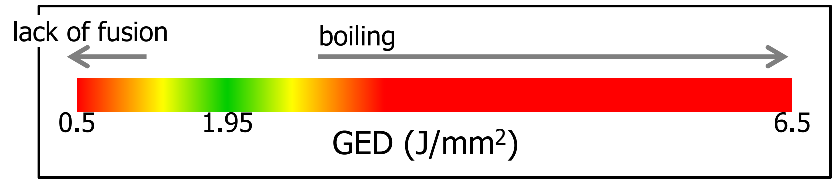
Direct Metal Laser Sintering (DMLS) of In718+

Optimized process parameters via design of experiments (DOE) and parameter quantification



DOE #3		
• Laser power (195 W) • Laser diameter (70 μm) • Laser speed (1,000 mm/s) • Hatch spacing (0.1 mm) • Stripe width (5 mm)	⇒	• Porosity (0.2 %) • Micro-cracking (0) • Gamma prime grain size (100 μm) • Yield strength (930 MPa)

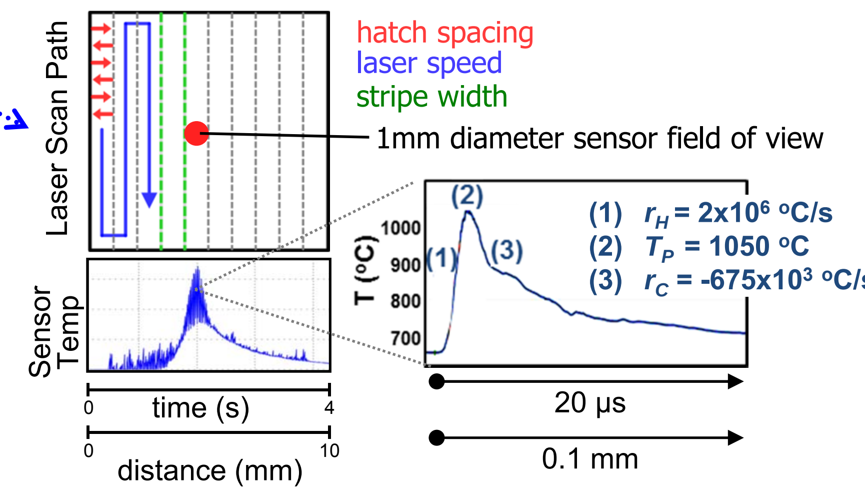
Global Energy Density (GED) defined: energy input density (J/mm^2) as laser beam is rastered across powder bed surface at constant speed



three given values are accurate, but distribution is still notional

Real Time Monitoring implemented and **In-Process Quality Assurance** under development

- In situ sensors record heating rate (r_H), peak temperature (T_P) and cooling rate (r_C) for each consolidated layer
- Quality metric (QM) for each build layer extracted, and process screening possible via comparison to QM limit baseline



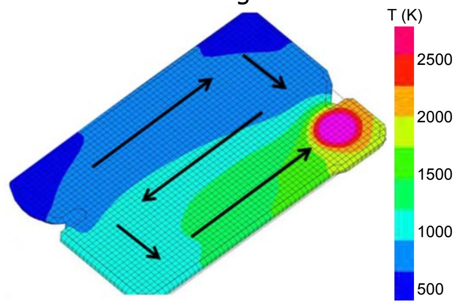
Process-microstructure-performance modeling for additive manufacturing

Direct Metal Laser Sintering (DMLS) Integrated Computational Materials Engineering (ICME) Framework

Finite difference physics process models predict location-specific thermal history of consolidated part:

- Gaussian moving heat source
- Melt pool with incorporated heat transfer, liquid radiation, and surface tension effects
- Cooling rate ~10^6 °C/s

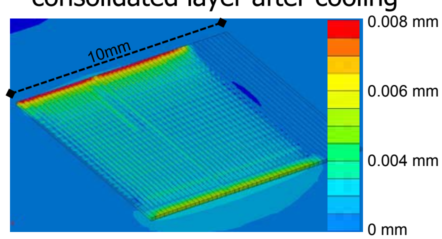
Temperature distribution from moving heat source during consolidation



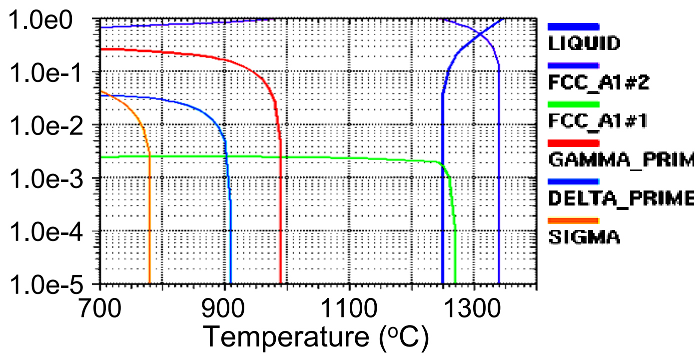
Microstructural models incorporate location-specific thermal history and predict

- Accumulated residual stresses
- Displacements
- strain hardening due to yielding
- Phase concentrations
- Grain size prediction dev underway

Displacement of single consolidated layer after cooling

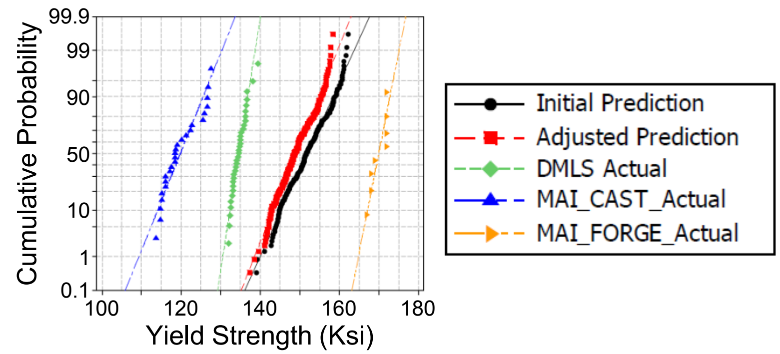


Phase concentration during cooling from melt



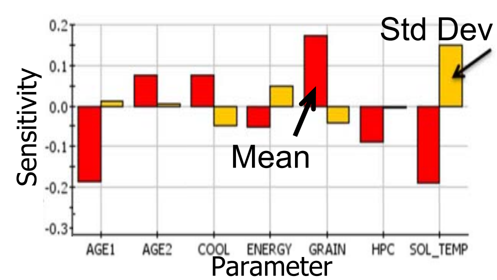
Yield strength prediction tool under development

- DMLS In718+ strengths significantly better than cast but much lower than forged
- Further incorporation of additive microstructural artifact effects needed



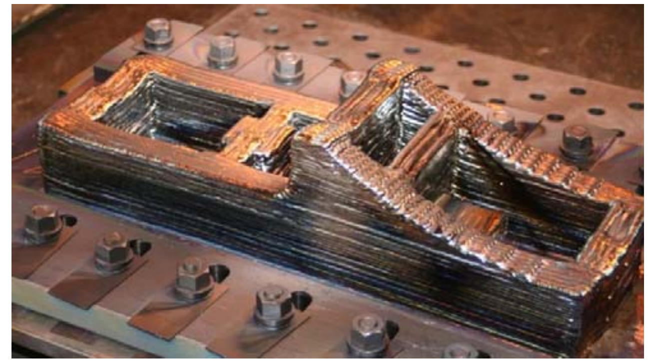
Qualification framework and uncertainty quantification indicates sensitivity for processing-property relationships

- Tensile properties are mostly driven by heat treatment (HIP, anneal, etc.)



Predict location-specific behavior of parts produced using directed energy deposition additive manufacturing

Electron Beam Direct Manufacturing (EBDM)



Combines electron beam welding technology with additive manufacturing principles and computer-aided design (CAD) to fabricate titanium shaped products.

- Large structural parts deposited (9’x4’x4’ build envelope) at high rate (7-20 lb/hr)
- Reduced material costs and buy-to-fly ratio
- Reduced machining time by up to 80%
- Elimination of costly tooling

Fully explore EBDM process window with scientific process models and minimal testing to determine the key parameters that impact quality of manufactured product

Informatics Methodology

Probabilistic Parameterization

12 processing parameters

Material Measurements

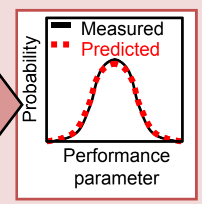
11 parameters measured

E-Beam Process Monitoring

Robust Computational Process and Design Tools

Process Models

- Phenomenological Metallurgical Principles
- Neural Net Analysis
- Genetic Algorithm Optimization
- Monte Carlo sampling of probabilistic process parameters
- Prediction of Yield Strength based on processing parameters



Component Definition

Certification Process

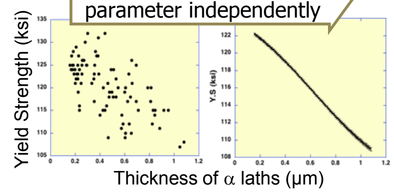
Predict location-specific behavior of titanium part produced using Electron Beam Direct Manufacturing (EBDM)

Informatics Methodology

- 270+ lbs Ti deposited and 1750+ test coupons from materials qualification effort
- 12 measured process parameters (e.g., beam energy distribution)
- 11 measured material parameters (e.g., alpha grain size)

Identify important relationships and general form using neural net analysis

Mathematically vary one parameter independently

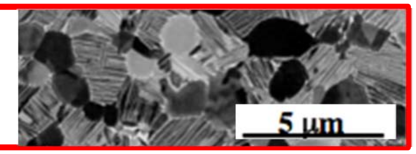


Robust Computational Process and Design Tools

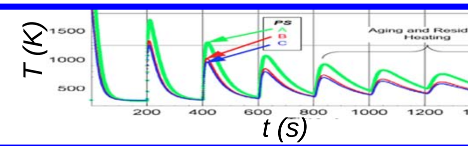
Link process parameters to microstructure and microstructure to material properties using metallurgical relationships

$$\sigma_{ys} = \sigma_o + \sigma_{ss} + \sigma_{ppt} + \sigma_{disp} + \boxed{\sigma_{gb}} + \sigma_{interface}$$

$$\sigma_{gb} = \sigma_o + \frac{k_y}{\boxed{\sqrt{d}}}$$



$$d = f(T,t)$$



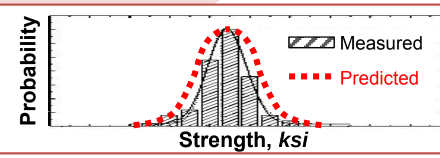
Measure T and t

Model Optimization

- Use measured EBDM inputs and genetic algorithms to optimize yield strength model
- The more data that is collected, the further optimized the model will become

Predict probabilistic tails in high fidelity

- Simulate process parameters using Monte Carlo techniques
- Compute Yield Strength using optimized science-based model for the entire process window

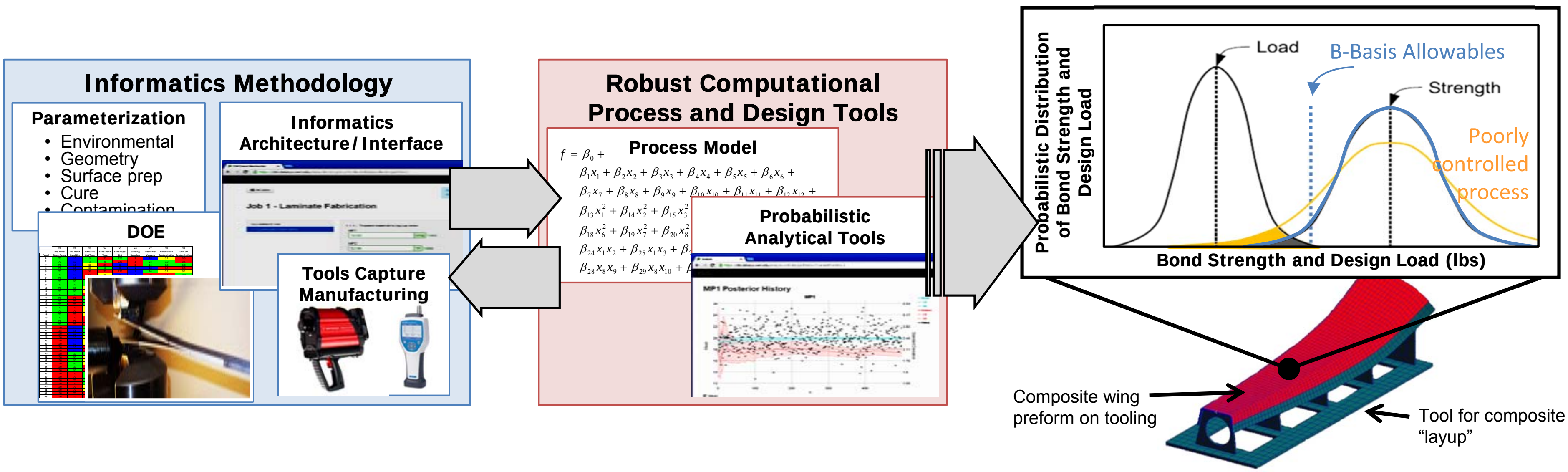


Conduct minimal testing to train the model

Combine model with probabilistic sampling of process conditions to predict tails with high fidelity

Probabilistic process control for bonded composite structures

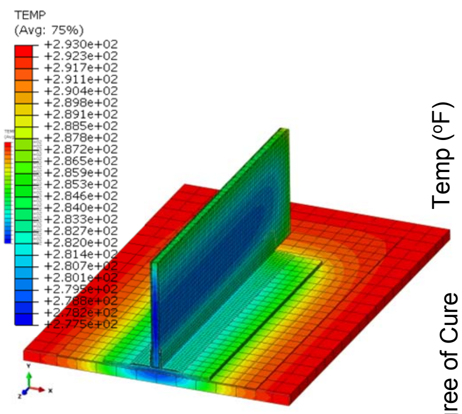
Combination of data science and engineering reliability analysis

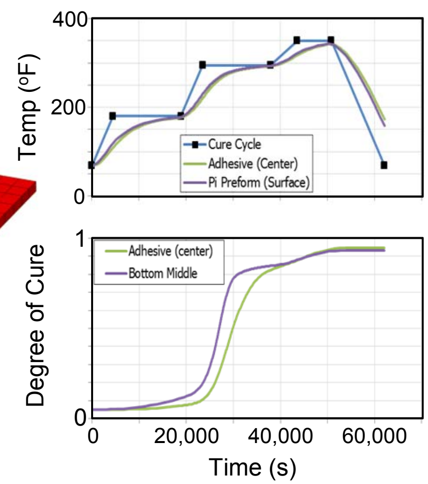


- Bayesian methods combine a priori models with observed shop floor data to:
  - iteratively inform models,
  - compute confidence, and
  - enable enhanced bond process control
- Informatics system records comprehensive set of factory floor parameters and visually displays knowledge of process
- Cure cycle modeling
- Prototype system being proven out using DCB coupon strengths as measured output

Probabilistic process control for bonded composite structures

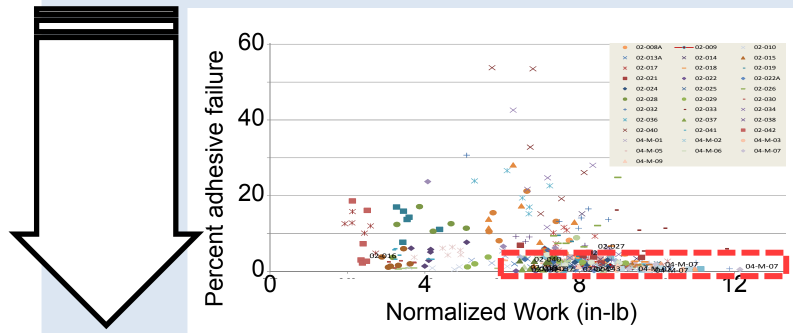
- Identified over 500 manufacturing parameters that drive quality of bond
- Evaluated 309 double cantilever beams (DCB) to identify critical parameters that determine bond strength
- Identified classes of contaminants:
  - silicones and fluorocarbons – surface affinity
  - hydrocarbon oils – soluble in adhesive
- Cure cycle physics of DCB and Pi joints modeled





Pi joint temperature distribution and degree of cure

Back-end tools extract informatics data



GOAL: Bayesian methods combine a priori models with observed shop floor data to:

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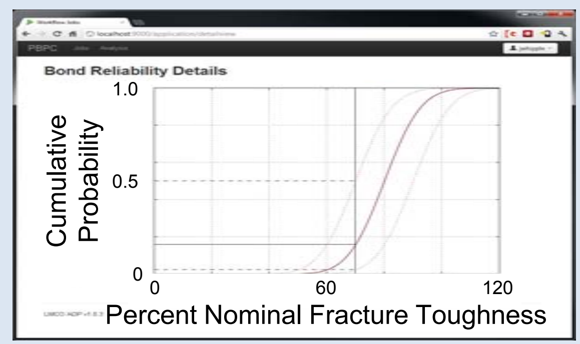
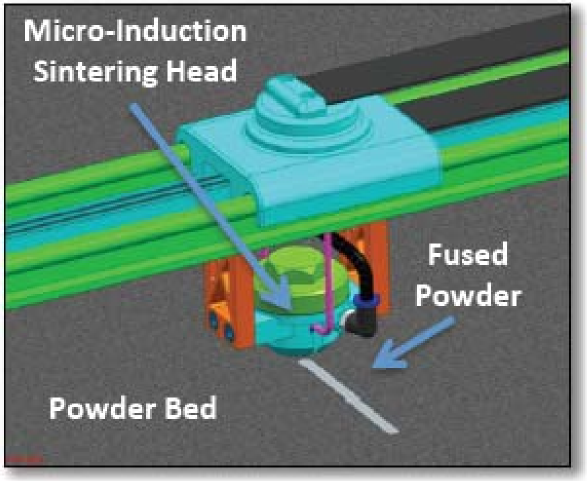


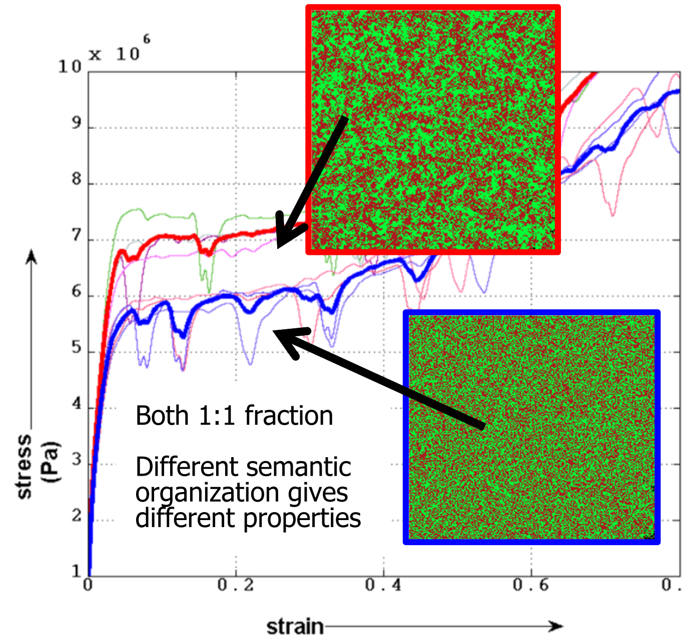
Building ability to predict bond quality as a function of manufacturing process

OM projects develop new additive processes and design approaches



Grid-Logic's Micro-Induction Sintering (MIS)

- Focused, high frequency induction heating to consolidate metal and metal matrix composite powders for 3D additive manufacturing
- Heating is tuned to specific material by theoretical optimization of frequency, field strength and powder morphology



Cornell University's Matter Compiler

Data-driven neural network approaches for designing optimized:

- macrostructures and
- multi-material microstructures

OM has established manufacturing demonstration facilities

DARPA's Manufacturing Demonstration Facilities (MDF) at **Penn State University Applied Research Laboratory** and **Army Research Laboratory Aberdeen Proving Grounds**

Infrastructure, expertise, and web portal

Demonstrations

Work with Defense and Commercial Industry as a trusted agent to independently demonstrate designs, manufacturing processes and manufactured products

Promote, disseminate, and sustain the application of AM technologies

Workshops, conferences, internships, education, and direct industry collaboration

Advancement of engineering capabilities and the understanding of AM technologies

- Curation, assessment, and validation of models
- Accelerating qualification through parameterized process data schema, data archiving, MMPDS protocol, and model interoperability standards
- Advanced design, analysis, and simulation tools
- A controlled, cyber-based, system enabling industry use of internal and external tools

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